NIH-PA Author Manuscript
NIH-PA Author Manuscript

Published in final edited form as:
J Occup Environ Hyg. 2011 June ; 8(6): 375–386. doi:10.1080/15459624.2011.583488.

Development of Solvent Exposure Index for Construction Painters

S.W. Wang[1], **H. Qian**[2], **C. Weisel**[2], **C. Nwankwo**[2], and **N. Fiedler**[2]

[1]Graduate Institute of Environmental Health, National Taiwan University, Taipei, Taiwan

[2]University of Medicine and Dentistry of New Jersey (UMDNJ), Robert Wood Johnson Medical School, Piscataway, New Jersey

Abstract

This article describes methodological approaches for reconstructing long-term occupational exposure to organic solvents among construction painters. A detailed exposure questionnaire was administered to 125 painters to develop a job exposure matrix (JEM). The questionnaire inquired about painting activities with solvent-based paints and use of protection equipment for the previous 25 years in 5-year intervals. Current and historical distributions of solvent air concentrations were assessed for the same time period based on the following information: industrial hygiene measurements, paint composition changes, and VOC emission rate changes from architectural and industrial maintenance coatings. Changes in protection factors of respirators were also assessed. A cumulative solvent exposure index was calculated for each painter through Monte Carlo simulations by combining appropriate input distributions of solvent air concentrations and protection factors of respirators with JEM. Sensitivity simulations revealed that the historical variations in solvent air concentrations had a higher impact on the cumulative solvent exposure index than changes in protection factors for respirators. Fifty-eight percent of painters were classified with a different exposure quartile when the solvent exposure index was used vs. an exposure based only on years using solvent-based paints, suggesting the need for more detailed exposure analysis than just years working when conducting epidemiologic studies for this worker population.

Keywords

exposure; modeling; organic solvents; painters

Introduction

Construction painters are regularly exposed to solvents from oil-based paints, which are still widely used in steel bridge and storage tank maintenance. Reconstruction of exposure often contributes the highest uncertainty in epidemiologic studies and can vary in occupational studies from using the number of years worked, to detailed exposure estimates based on

Correspondence to: Sheng-Wei Wang, National Taiwan University, Graduate Institute of Environmental Health, No. 17 Xuzhou Rd., Taipei 100, Taiwan; mumumi@gmail.com.

individual questionnaires about activities, combined with historical air concentration measurements.[1–3]

In general, exposure assessment methods in occupational studies often include the following approaches: subject-reported job histories and air concentration associated with specific jobs, job-specific questionnaires, and job-exposure matrices (JEMs).[4,5] Subject-reported job histories and job-specific questionnaires are used to derive worker's exposure duration. JEMs are produced by combining a series of job titles with the information of a list of exposure agents. The cells of the matrix indicate the presence, intensity, frequency, or probability of exposure to a specific agent in a specific job title.[6]

When chemical exposure data—such as measurements from exposure databases and work site or personal measurements among study subjects—are available, they can be used to improve quantification of exposure. A cumulative lifetime exposure index can be derived by combining chemical measurements and JEMs and has been used in several previous studies of painters and workers at paint manufacturing companies.[7–9]

The other approach for improving exposure quantification is to design exposure questionnaires to ascertain key determinants of exposure. For example, Fidler et al.[10] developed a detailed questionnaire focusing on the amount of time spent in different painting-related activities, modified by the use of protective equipment to specify lifetime cumulative exposure among commercial, residential, and industrial structural painters. This questionnaire, and others developed in Europe and Japan, have been applied in several studies of painters.[7–13]

There are other challenges in reconstructing solvent exposures that have not been adequately addressed. The range of solvent air concentrations measured for any individual task and paint type (water- or oil-based) is wide[14–16] and needs to be considered when assigning a single exposure value. In addition, the composition of paint has changed over the last several decades.[10,15,17] Therefore, it is essential to characterize the historical trend of solvent air concentrations to accurately reconstruct solvent exposures to painters. Further, the protection factor for protective equipment (such as respirators) has been improved over the years. The corresponding temporal changes of protection factors also need to be considered in solvent exposure reconstruction.

The objective of the present study was to reconstruct lifetime solvent exposures for construction painters by incorporating (1) job histories of painting activities through a detailed exposure questionnaire, (2) industrial hygiene measurements of current solvent air concentrations, and (3) historical trends of solvent air concentrations and protection factors of respirators. The reconstructed solvent exposures evaluate average exposures over 5-year time periods summed over a lifetime of employment. These average exposures include neither agents for which the biological mode of action requires acute exposures above a specific threshold, nor the issue of latency between the exposure and health outcome. A more detailed solvent exposure reconstruction would be needed to address these issues.

The hypothesis in the present study was that incorporating solvent air concentrations, the respirator protection factor, and their historical trends for exposure reconstruction would significantly alter exposure classification relative to classifications based solely on years of working with solvent-based paints. It is recognized that uncertainty in the responses by the painter concerning the amount of time spent painting by each technique and use of respiratory protection would also add to the uncertainty in the exposure index, but that component of uncertainty was not examined.

Methods

Painting Questionnaire

As part of an epidemiologic study assessing the effects of chronic solvent exposure on neurobehavior, 125 construction painters were recruited from New Jersey, New York, and Pennsylvania. A questionnaire was administered to painters to collect information on the use of solvent paints and protective equipment worn during 5-year intervals from 1980 to 2005. Key information collected included the number of years painting with solvent-based paints (SBP); the number of months worked per year; the number of hours worked per week; the portion of time spent painting by different techniques (spray, roller, brush, rag/sponge, and cleaning equipment); and whether a respirator was used and, if so, which type of respirator (dusk mask, half-face chemical cartridge respirator, full-face chemical cartridge respirator, supplied-air respirator) was worn and how often. Painters were asked to provide averaged or typical answers to the above questions over 5-year intervals. Rather than using a printed version of this questionnaire, a computerized version was developed and built into the platform of Microsoft Access database format. To help subjects recall what they were doing for each particular 5-year time period, a table of life events (e.g., marriage, birth of a child) was created for them to fill out first. The advantage of the computerized questionnaire was that constraints on questions were imposed to ensure that only physically meaningful answers were provided, questions were not skipped, and questionnaire data were automatically saved in database format after subjects finished answering the questions.[18] A trained technician administered the questionnaire and recorded the answers to ensure the integrity of the data.

Exposure Reconstruction Modeling Methodology

Table I presents the list of solvent exposure reconstruction modeling components that were considered in the current study. The details of how these components were determined follow.

Cumulative Time Spent Painting—The number of years painting with SBP was used as the first estimate for cumulative time spent painting. However, since solvent exposures vary greatly with painting activities (such as spraying, rolling, brushing, rag/sponge, and cleaning), the activity-specific painting time was calculated by summing the percentages of time spent for different activities multiplied by the amount of time across the 5-year intervals that the subject indicated he was painting with SBP. The questionnaire data provided qualitative responses for the time spent for different activities (such as all the time, more than half the time, about half the time, less than half the time). Therefore, an assumption was made to convert qualitative responses to quantitative percentages in the current study as follows: all the time (100%), almost all the time (90%), more than half the time (75%), about half the time (50%), less than half the time (25%), a little of the time (10%), and never (0%).

Air Concentrations of Organic Solvents—The composition of solvent-based paints has changed over the years as improved formulations have been developed to comply with the U.S. Environmental Protection Administration (USEPA) regulations. Volatile organic compound emissions from industrial paint were reduced to control ozone formation.[19,20] Thus, to develop a lifetime exposure index, it is essential to characterize the changes of solvent air concentrations over time due to the impact of paint composition changes. The following approaches were used in the current study to characterize the historical changes of solvent air concentrations:

- Examination of current industrial hygiene measurements of solvent air concentrations. Current industrial hygiene measurements were obtained from a companion field study that provided personal air measurements of organic solvent concentrations for bridge painters working in New Jersey and New York, for specific painting activities, and for an entire workday.[21]
- Literature searches were conducted for finding the historical industrial hygiene measurements of organic solvent concentrations based on the following databases: PubMed, TOXLINE, Health Hazard Evaluation (HHE) studies from the National Institute for Occupational Safety and Health (NIOSH), Electronic Library of Construction Occupational Safety & Health (ELCOSH), Federal Highway Administration (FHA) publications, the *Journal of Protective Coatings & Linings*, National Paints and Coatings Association (NPCA), and Engineering Village. Collected literature over different time periods were merged together with current measurements for assessing the historical changes of solvent air concentrations.
- Examination of the VOC emission reductions from industrial paint and the associated historical trend of VOC emission estimates: The USEPA has issued a series of regulations to restrict VOC emissions from architectural and industrial maintenance (AIM) coatings since 1990.[22] It is important to review the changes of VOC regulations on AIM coatings and to evaluate the impact of these changes on the VOC emissions from AIM coatings and their potential influence on the trend of historical changes of solvent air concentrations. Literature searches were conducted in the following resources: the USEPA, NPCA, Northeast Protective Coating Committee (NEPCOAT), and *Journal of Protective Coatings & Linings*. Technical reports, memoranda, and online information were collected.
- Examination of material safety data sheets (MSDSs) for current and past paint compositions and literature search for historical changes on paint composition.

Protection Factors of Respirators—One major modifying factor that reduces the dose resulting from an exposure concentration during painting is wearing protection equipment, such as a respirator. The reduction level was determined by the type of respirator used and amount of time a respirator was worn during different painting activities. To reduce high solvent air exposures, painters are required by the Occupational Safety and Health

Administration (OSHA) to wear respirators when spraying in a confined space.[(23)] The solvent exposure reconstruction considers only the volatile component of the paint. The reconstructed exposure would underestimate the exposure to painters who do spray painting while not wearing any respiratory protection, due to neglecting the possible exposure to solvent via droplet aerosol.

However, for brushing or rolling operations, respirators are not necessarily worn, since solvent air concentrations are much lower. Several types of respirators are commonly used in industrial painting operations, including dust masks, chemical cartridge (half- or full-face) respirators, and supplied air or power-purified respirators. The assigned protection factor associated with wearing a particular type of respirator was defined as the ratio of the ambient concentration of a given contaminant to that inside a respirator.[(24,25)] A literature search for current and historical assigned protection factors of different respirators was conducted in the following resources: the American National Standards Institute (ANSI), NIOSH, OSHA, PubMed, TOXLINE, and respirator manufacturers.

Calculation of Solvent Exposure Index—A solvent exposure index was calculated from the painting time (*T*), air concentrations of organic solvents (*C*), and contaminant collection efficiency for wearing protection equipment (*P*), using the following equation:[(26)]

$$Sol\ Exp=\sum_{i=1}^{n1}\sum_{j=1}^{n2}\sum_{k=1}^{4}\sum_{m=1}^{n3} C_{ijkm}\times T_{ijkm}\times(1-P_{ijkm}) \quad (1)$$

where

i, j, k, m are indices for year, month, week, and application method, respectively

C_{ijkm} is the air concentration of organic solvent (ppm)

T_{ijkm} is the painting time (hours per week)

P_{ijkm} is the contaminant collection efficiency of wearing respirator and dependent on the type of respirator worn (unitless)

The following steps were conducted for calculating the solvent exposure index for each painter.

1. The painter questionnaire data were preprocessed, extracting key variables associated with painting times and levels of protection used over 5-year intervals.
2. The number of years painting with SBP was divided by 5 to determine the number of the 5-year intervals ($n1$ in the first summation of Eq. 1) needed for each painter.
3. Within each 5-year interval, the number of working months ($n2$ in the 2nd summation of Eq. 1) was determined by multiplying the number of months worked per year with 5. The number of Monte Carlo simulations performed for each painter was based on the number of working weeks obtained by multiplying the number of working months with 4, assuming that painters worked all 4 weeks of a

working month (the 3rd summation in Eq. 1). For example, if a painter worked 12 months a year, 240 simulations were conducted for a 5-year period. Further, if the painter worked all 25 years, a total of 1200 simulations were performed for this painter.

4. Each Monte Carlo simulation was to assign the solvent air concentration (C_{ijkm} in Eq. 1) for each working week based on the painting application method and the associated distribution of solvent air concentrations for that painting application method. Distributions of solvent air concentrations were based on the personal air measurements collected from the bridge work sites,[21] along with the adjustment factor accounting for the paint composition changes estimated in the current study over the past 25 years.

5. For each working week, the number of hours worked per week was distributed into different durations (*Tijkm* in Eq. 1) according to the percentages of time spent painting for five different application methods (spray, roller, brush, rag/sponge, and cleaning equipment). Further, the information on the level of protection use (i.e., type of respirator and how often) was extracted and converted to the numerical value of contaminant collection efficiency (P_{ijkm}) according to the type of the respirator worn. Solvent exposure was then calculated by multiplying the assigned solvent air concentration (C_{ijkm}) with the exposure duration (*Tijkm*) and the penetration factor (1- P_{ijkm}) for each painting application method in a working week.

6. The calculated solvent exposures were summed together for all the painting application methods performed in a working week (the fourth summation of Eq. 1). Then, they were summed over all the working weeks of the painter's career (the first to the third summations of Eq. 1) to generate the cumulative solvent exposure index expressed in the unit of ppm-hours.

Results

Cumulative Time Spent Painting

Table II shows the number of painters in the cohort across 5-year time periods from 1980 to 2005, based on the number of years painting with SBP from the painting questionnaires. The questionnaire data were also used to assign for each painter the amount of time spent painting using five different techniques (spraying, rolling, brushing, rag/sponge, and cleaning) over 5-year time periods from 1980 to 2005. In general, the majority of painters spent their time in spraying, rolling, and brushing, while much less time was spent in cleaning or using a rag/sponge. The uncertainty associated with recall and estimating the time spent painting was not included in this study. Therefore, the uncertainty of the calculated exposure index was based solely on uncertainty with the exposure intensity, which would be an underestimation of the overall uncertainty.

Air Concentrations of Organic Solvents

Past and Current Industrial Hygiene Measurements—The air concentration term (C) in Eq. 1 was calculated using current exposure data for solvent and then adjusted for different time periods as described below, based on trends in the concentrations of the volatile components of paint. Current exposure data were taken from Qian et al.,[21] which measured personnel exposures to a mixture of organic solvents—including aromatics, acetates, and ketones that have neurotoxicant properties—for construction painters during specific painting techniques (Table III). The concentrations across the groups were summed together to obtain a total solvent exposure intensity. Current exposure concentration data were then adjusted retrospectively to obtain estimated historical exposure concentrations in developing the solvent exposure index, to overcome a major difficulty, the lack of past industrial hygiene measurements of painters in the United States. The adjustment factor was developed by assessing the general trend of available historical solvent air concentrations[13, 27–30] (Figure 1a).

One major finding was that the solvent air concentrations were approximately 3-fold higher before 1990 than after. No clear trend was observed for the studies in the 1990s to the present because of the variations in locations, size of study, and painting activity during the monitoring of solvent air concentrations.

VOC Regulation and Emission Trend—The 1999 National Air Quality and Emissions Trends Report of the USEPA[31] provided national estimates of total VOC emissions from surface coatings and from architectural and industrial maintenance coatings during the period 1989 to 1999. The 1994, 1998, and 2000 Current Industrial Reports of the U.S. Census Bureau[32] provided the national estimates of total shipment/sale quantity for (1) total paint and allied products, and (2) architectural and industrial maintenance coatings during 1989 to 1999, which can be used to match the corresponding VOC emission estimates of the USEPA for calculating the VOC emission rates in each year of the 10-year period. Based on the calculated VOC emission rates, a linear regression analysis was conducted to characterize the temporal trend of VOC emission rates from architectural and industrial maintenance (AIM) coatings (Figure 1b). The VOC emission rate has decreased about 17.3% nationally over the 10-year period from 1989 to 1999, with a regression coefficient (−0.0034, p-value < 0.0001) for an estimated 1.7% per year.

Examination of MSDSs and Paint Composition Changes—The MSDS online database (http://www.msdsonline.com) was searched for the VOC composition of the paints commonly used in bridge painting for the brand names provided by the painters recruited in the field measurement study. There were two major difficulties encountered in analyzing the information on paint compositions obtained from the MSDSs for characterizing the temporal changes of the VOC compositions. First, most of the MSDSs found were for after 1995, with very few available during 1990 to 1995, and none was found for materials used before 1990. Second, the MSDS provided only ranges of VOC compositions. We also conducted literature searches on paint composition changes due to the impact of VOC emission regulation in AIM coatings. However, the reports located discussed only qualitatively how AIM coatings were reformulated to use solvents not on the Hazardous Air Pollutant (HAP) list, or by increasing the solid content, rather than quantitatively documenting the changes in VOC compositions. Therefore, the historical trend of solvent air concentrations was estimated based on the linear regression results from emission rate data.

Historical Trend of Solvent Air Concentrations—The estimated annual VOC emission reduction rate of 1.7% per year for architectural and industrial maintenance coatings (Figure 1b) was used as a surrogate for the temporal change of solvent air concentrations in construction painting for the time period after 1990. The solvent air concentrations before 1990 were assumed to be 3-fold higher than the concentrations after 1990, based on the general trend shown in Figure 1a. Thus, the historical solvent air concentrations for each 5-year interval of the previous 25 years were estimated by adjusting the current industrial hygiene measurements[(21)] with the temporal trend factors obtained above.

Current and Historical Protection Factors of Respirators

Solvent protection factors for a large number of respirators were evaluated by NIOSH in the late 1970s by considering various working conditions during paint spraying as well as how well the respirator fit during painting.[(33)] Average contaminant collection efficiency for chemical cartridge respirators was approximately 65%, while the contaminant collection efficiency for supplied air respirators was approximately 90%.[(10)] Dust masks were considered as providing no protection, since they do not trap and retain solvent vapors. Fidler et al.[(10)] and Burstyn and Kromhout[(26)] have used these protection factors in their estimation of long-term solvent exposure index for construction painters.

The standard for respiratory protection published by ANSI in 1980 (ANSI Z88.2–1980)[(34)] listed the first standard of assigned protection factors for respirators. In 1992, ANSI updated the assigned protection factors of respirators in ANSI Z88.2–1992,[(34)] based on a review of the available studies on respirator performance. The updated assigned protection factors of 10, 50, and 1000 were indicated for half-face chemical cartridge, full-face chemical cartridge, and supplied-air respirators, respectively, corresponding to 90%, 98%, and 99.9% contaminant collection efficiencies. Respirator manufacturers confirmed that these assigned protection factors are still valid for the respirators used currently. Table IV summarizes the current and historical contaminant collection efficiencies of four types of respirators (dust mask, half-face chemical cartridge, full-face chemical cartridge, and supplied air respirator) used in the current study.

Solvent Exposure Index

Solvent exposure indices were calculated for 125 painters based on the above specified inputs. Figure 2 shows the cumulative distribution function (CDF) of the calculated solvent exposure indices. There are three major factors contributing to the calculated lifetime solvent exposure index: (1) number of years using SBP, (2) proportion of time spent spraying compared with other application methods, and (3) level of protection used. The painter with the highest solvent exposure index (52.1×10^6 ppm-hours) applied solvent-based paints for 25 years by spraying while wearing a dust mask as his only protection. The CDF plot shows the range of the distribution of solvent exposure indices covering approximately four orders of magnitude from 5.0×10^3 ppm-hours to 52.1×10^6 ppm-hours.

The calculated solvent exposure indices were based on a reconstruction of the lifetime solvent exposure that has accounted for all the relevant factors (denoted as *Solvent air* and

Protection factor). To evaluate the differences in exposure classifications by using the less detailed information for solvent exposure reconstruction, the following scenarios were considered:

- *The number of years*. Solvent air concentrations and respirator protection factors were not considered.
- *Solvent air adjusted*. Solvent air concentrations were adjusted for historical changes, but protection factors of respirators were not adjusted for historical changes (i.e., current protection factors used throughout).
- *Protection factor adjusted*. Protection factors of respirators were adjusted for historical changes, but solvent air concentrations were not adjusted for historic changes (i.e., current solvent air concentrations used throughout).

A comparison of *Solvent air* and *Protection factor* vs. *Solvent air adjusted* should therefore reveal the impact of not considering historical adjustments for respirator protection factors on the calculated solvent exposure index; while a comparison of *Solvent air* and *Protection factor* vs. *Protection factor adjusted* should reveal the impact of not considering historical adjustments for solvent air concentrations on the calculated solvent exposure index.

For evaluating the differences in exposure classifications generated by different levels of solvent exposure estimates, a two-way classification table was created by assigning painters to different exposure quartiles (Table V). First, the painters were classified in the four quartiles based on the exposure indices of *Solvent air* and *Protection factor* in the horizontal direction of the table. Within each quartile, the painters were classified again in the vertical direction of the table, based on the exposure indices generated with less detailed information, such as *the number of years*, *Solvent air adjusted*, and *Protection factor adjusted*. If the classifications based on both directions of the table are the same, the painters would be distributed evenly into the four diagonal cells.

Painters were spread out in each column of the quartiles specified by *Solvent air* and *Protection factor* into different quartiles specified by *the number of years*. For instance, there were 31 painters classified in the first quartile (i.e., the 25th percentile) according to *Solvent air* and *Protection factor*, but there were only 15 painters out of these 31 painters classified in the 1st quartile again, based on *the number of years*. The other 16 painters were classified into the 2nd, 3rd, and 4th quartiles (N = 10, 5, and 1, respectively). There were a total of 53 painters out of 125 painters classified in the four diagonal cells of the two-way classification table, indicating that *the number of years* can capture about 42% of the quartile classification based on *Solvent air* and *Protection factor*. The exposure classifications for the other 58% of the painters, based on *the number of years*, were different from those based on *Solvent air* and *Protection factor*.

For the comparisons of *Solvent air* and *Protection factor* vs. *Protection factor adjusted* and *Solvent air* and *Protection factor* vs. *Solvent air adjusted*, there were 111 painters (about 89% of 125 painters) and 115 painters (92% of 125 painters) classified in the four diagonal cells, respectively. Therefore, the quartile classification was shifted for about 50% of the subjects by including solvent air concentrations and respirator protection factors as compared to *the number of years*. The differences in exposure quartile classification observed for *Protection factor adjusted* (about 11%) and *Solvent air adjusted* (about 8%) were due to the impact of not considering historical adjustments for solvent air concentrations and respirator protection factors, respectively. Spearman correlation coefficients were also calculated for the above three sets of comparisons (Table V). The highest correlation (0.99) was observed in *Solvent air* and *Protection factor* vs. *Solvent air adjusted*, while the lowest correlation (0.55) was in *Solvent air* and *Protection factor* vs. *the number of years*, a similar trend revealed in the two-way classification table.

To further investigate the impact of not considering historical adjustments for the solvent air concentrations, the solvent exposure indices generated with and without the adjustments were directly compared with each other within each exposure quartile (Figures 3 and 4). The inclusion of historical adjustments for the solvent air concentrations generally resulted in higher exposure indices relative to those not considering the adjustments. This trend was more clearly shown for the painters in the 3rd and 4th exposure quartiles (Figure 3) than in the 1st and 2nd exposure quartiles (Figure 4). For better quantifying the impact on the exposure index, the numbers of painters having greater than a 2-fold increase in the exposure indices due to the inclusion of adjustments were counted for each exposure quartile. These numbers were 20, 8, 7, and 1, respectively, for the 4th, 3rd, 2nd, and 1st exposure quartiles. Therefore, the inclusion of historical adjustments for the solvent air concentrations had bigger impact on the exposure indices of painters classified in the higher exposure quartiles (i.e., the 3rd and 4th quartiles). The common characteristics of the painters having greater than a 2-fold increase in the exposure indices were that they generally had more than 20 years of using SBP and also spent a significant amount of time in painting activities (especially in spraying) before 1990.

The impacts of including historical adjustments for the respirator protection factors were also further revealed by comparing the solvent exposure indices generated with and without the adjustments (Figures 5 and 6). Since the historical adjustments were to reduce the respirator protection factors before 1990 (Table IV), the inclusion of these adjustments also resulted in higher exposure indices relative to those not considering the adjustments. However, the rates of increases were smaller than those caused by the inclusion of historical adjustments for the solvent air concentrations (see the comparisons of Figures 5 vs. 3 and Figures 6 vs. 4).

Further, the painters with bigger increases in the exposure indices were mostly revealed in the 2nd and 3rd exposure quartiles. Common characteristics of these painters were that they generally had at least 20 years of using SBP (i.e., the time period before 1990 was covered) and had used respirators extensively. Therefore, the impact of applying the adjustments for the protection factors of respirators was more significant among these painters.

Discussion

The most important contributors to the solvent exposure index were the solvent air concentrations of different painting methods (i.e., spraying, rolling, and brushing) and the amount of time spent using these methods. There were large differences in the solvent air concentrations between these painting methods, where the concentrations of spraying were about two orders of magnitude higher than rolling and brushing (Table III). Therefore, the amount of time spent spraying was a dominant factor in the solvent exposure indices of the painters. The variable of years painting with SBP could provide only the total time of painting but could not differentiate the amount of time spent using different application methods and the association of these methods with estimated solvent air concentrations.

Use of respirators by the painters during different painting methods was also considered in the calculation of the exposure index. Historical data of how the painters used respirators in different painting methods were collected for the previous 25 years, in 5-year intervals. Percentages of the painters wearing respirators almost all the time while spraying were always higher than the percentages in rolling/brushing (Table VI). However, the contribution to the exposure index from spraying and wearing a respirator was still higher than the contribution from rolling/brushing without wearing a respirator. This was due mainly to the large differences in solvent air concentrations between spraying and rolling/brushing, which overcame the impact of respirator use in determining the exposure index.

The impact of including historical adjustments for the solvent air concentrations was greater than for the respirator protection factors on the exposure index, due mainly to the larger extent of adjustment for the solvent air concentrations (i.e., 3-fold higher before 1990) than the adjustments for the protection factors of respirators (generally 25% lower before 1990). The impact of including historical adjustments for the solvent air concentrations was revealed mostly among the painters in the 3rd and 4th exposure quartiles who generally conducted extensive painting activities (especially in spraying) before 1990. However, the impact of including historical adjustments for the respirator protection factors was revealed mostly among the painters in the 2nd and 3rd exposure quartiles. Generally, painters in the 4th exposure quartile rarely or never used respirators when painting, prior to 1990. Thus, the adjustments for the respirator protection factors had very little or no impact on painters in the 4th quartile. The painters in the 1st quartile generally had less than 20 years' experience painting with SBP. Therefore, adjustments for the time period before 1990 had very little or no impact for these painters.

The historical trend of the respirator use while spraying, rolling, and brushing was also examined (Table VI). The percentage of time respirators were worn for all three painting methods for the time period before 1990 was lower than after 1990. However, the percentages of the painters wearing respirators in spraying before 1990 decreased more rapidly than the percentages in rolling/brushing, since even after 1990 few painters wore respirators during rolling/brushing. Thus, the spraying activities in the time periods before 1990 caused more solvent exposures than after 1990, due both to contributions from the increased solvent air concentrations and reduced protection.

The major historical change in solvent air concentrations found in this study was that the solvent air concentrations before 1990 were three times the concentrations after 1990. This trend was generally consistent with the study of Caldwell et al.,[35] where the trend of 4-fold reduction was reported for hydrocarbon solvent exposures from 1960 to 1998. The estimated temporal trend of solvent air concentrations was used to adjust the current solvent air concentration measurements for calculating the cumulative solvent exposure index. The current solvent air concentration measurements were taken from personal air samples of painters conducting spraying, rolling, and brushing in the field.[21] However, these measurements could overestimate the actual daily solvent exposures of the painters, since the lower exposures experienced by the painters from the time when they were taking breaks were not taken into account.[21]

Previous studies have used subsets of the details described above for assessing occupational exposures to organic solvents.[7–10,13,15,26,36] Several studies conducted industrial hygiene measurements to be combined with JEMs for deriving a lifetime exposure index.[8–9,13,36] However, historical trends of solvent air concentration were not considered in those studies. Kishi et al.[15] have incorporated the historical changes of solvent air concentrations for estimating solvent exposure indices, but protective equipment use was not considered. Other studies that have considered the use of protective equipment for modifying exposure[7,10] based on point estimates (i.e., averages) to represent solvent air concentrations or the quantities of paint used.

The present study took into account all of the relevant solvent exposure factors in reconstructing lifetime solvent exposures for construction painters: the historical trends in solvent air concentrations and respirator protection factors, and the variability of solvent air concentrations. Since the true occupational lifetime solvent exposures for the painters were not known, validation of the solvent exposure estimates could not be conducted directly. However, through the subsequent epidemiologic investigation of exposure-response relationships, the exposure estimates can be indirectly validated by linking with the neurobehavioral test results of the painters. The best solvent exposure estimate can be identified from the strongest exposure-response association revealed in the epidemiologic investigation. Other agents that can affect the neurobehavioral outcomes, such as exposure to lead in paint either during application or when stripping lead-based paint from surfaces, alcohol consumption, and drug use, must also be considered in addition to the solvent exposure calculated here.

Conclusions

Cumulative solvent exposure indices were developed for construction painters by combining appropriate input distributions of solvent air concentrations and protection factors of respirators with JEM. Sensitivity simulations revealed that the historical variations in solvent air concentrations had a higher impact on the cumulative solvent exposure index than changes in protection factors for respirators. Fifty-eight percent of painters were classified with a different exposure quartile when the solvent exposure index was used vs. an exposure based only on years using SBP, suggesting the need, for this worker population, for more detailed exposure analysis than just years working.

Acknowledgments

Support for this study has been provided by the National Institute for Occupational Safety and Health (Grant #R01 OH08198) and NIEHS center grant (Grant #P30 ESO5022).

The viewpoints expressed in this work are solely the responsibility of the authors and do not necessarily reflect the views of NIOSH and NIEHS or their contractors.

References

1. Blair A, Stewart PA. Do quantitative exposure assessments improve risk estimates in occupational studies of cancer? Am J Ind Med. 1992; 21(1):53–63. [PubMed: 1553986]
2. Kauppinen TP. Assessment of exposure in occupational epidemiology. Scand J Work Environ Health. 1994; 20:19–29. [PubMed: 7846489]
3. Nieuwenhuijsen MJ. Exposure assessment in occupational epidemiology: Measuring present exposures with an example of a study of occupational asthma. Int Arch Occup Environ Health. 1997; 70(5):295–308. [PubMed: 9352332]
4. Tielemans E, Heederik D, Burdorf A, et al. Assessment of occupational exposures in a general population: Comparison of different methods. Occup Environ Med. 1999; 56(3):145–151. [PubMed: 10448321]
5. Teschke K, Olshan AF, Daniels JL, et al. Occupational exposure assessment in case-control studies: Opportunities for improvement. Occup Environ Med. 2002; 59(9):575–593. [PubMed: 12205230]
6. Hoar S. Job exposure matrix methodology. J Toxicol Clin Toxicol. 1983; 21(1-2):9–26. [PubMed: 6672226]
7. Glass DC, Spurgeon A, Calvert IA, Clark JL, Harrington JM. Retrospective assessment of solvent exposure in paint manufacturing. Occup Environ Med. 1994; 51(9):617–625. [PubMed: 7951794]
8. Jang JY, Lee SY, Kim JI, Park JB, Lee KJ, Chung HK. Application of biological monitoring to the quantitative exposure assessment for neuropsychological effect by chronic exposure to organic solvents. Int Arch Occup Environ Health. 1999; 72(2):107–114. [PubMed: 10197482]
9. Lee CR, Jeong KS, Kim Y, Yoo CI, Lee JH, Choi YH. Neurobehavioral changes of shipyard painters exposed to mixed organic solvents. Ind Health. 2005; 43(2):320–326. [PubMed: 15895847]
10. Fidler AT, Baker EL, Letz RE. Neurobehavioral effects of occupational exposure to organic solvents among construction painters. Br J Ind Med. 1987; 44(5):292–308. [PubMed: 3496112]
11. Riala R, Kalliokoski P, Pyy L, Wickstrom G. Solvent exposure in construction and maintenance painting. Scand J Work Environ Health. 1984; 10(4):263–266. [PubMed: 6494847]
12. Kromhout H, Oostendorp Y, Heederik D, Boleij JS. Agreement between qualitative exposure estimates and quantitative exposure measurements. Am J Ind Med. 1987; 12(5):551–562. [PubMed: 3687951]
13. [Accessed July 12, 2007] Development of an Exposure Matrix for Construction Painters Based on Specific Work Tasks. [Online] http://www.cdc.gov/nioshtic-2/
14. Cherry N, Hutchins H, Pace T, Waldron HA. Neurobehavioral effects of repeated occupational exposure to toluene and paint solvents. Br J Ind Med. 1985; 42(5):291–300. [PubMed: 3872680]
15. Kishi R, Harabuchi I, Katakura Y, Ikeda T, Miyake H. Neurobehavioral effects of chronic occupational exposure to organic solvents among Japanese industrial painters. Environ Res. 1993; 62(2):303–13. [PubMed: 8344237]
16. Fiedler N, Weisel C, Lynch R, et al. Cognitive effects of chronic exposure to lead and solvents. Am J Ind Med. 2003; 44(4):413–23. [PubMed: 14502770]
17. Wieslander G, Norback D, Edling C. Occupational exposure to water based paint and symptoms from the skin and eyes. Occup Environ Med. 1994; 51(3):181–186. [PubMed: 8130846]
18. Weisel CP, Weiss SH, Tasslimi A, Alimokhtari S, Belby K. Development of a Web-based questionnaire to collect exposure and symptom data in children and adolescents with asthma. Ann Allergy, Asthma, Immunol Ann Allergy, Asthma, Immunol. 2008; 100(2):112–119.
19. Hare CH. VOC compliance. J Protective Coatings & Linings. Jul.2001 :57–66.
20. Huffman L. Going green: Raw materials suppliers weigh in on low VOC and high-solids coatings for industrial maintenance. J Protective Coatings & Linings. Apr.2007 :30–35.
21. Qian H, Fiedler N, Moore D, Weisel CP. Occupational exposure to organic solvents during bridge painting. Ann Occup Hyg. 2010; 54(4):417–426. [PubMed: 20354053]

22. Kapsanis K. Several states adopted VOC limits below federal levels: First in a series on coatings regulations. J Protective Coatings & Linings. Oct.2005 :36–42.
23. Respiratory Protection. Code of Federal Regulations Title 29, Parts 1910 and 1926. 2009:419–445.
24. Nelson TJ. The assigned protection factor according to ANSI. Am Ind Hyg Assoc J. 1996; 57:735–740. [PubMed: 8765202]
25. Nicas M, Neuhaus J. Variability in respiratory protection and the assigned protection factor. J Occup Environ Hyg. 2004; 1:99–109. [PubMed: 15204884]
26. Burstyn I, Kromhout H. Trends in inhalation exposure to hydrocarbons among commercial painters in The Netherlands. Scand J Work Environ Health. 2002; 28(6):429–438. [PubMed: 12539803]
27. [Accessed July 18, 2008] Health Hazard Evaluation report (HETA 86-441-1913), Monark Boat Company, Arkansas (1988). [Online] http://www.cdc.gov/niosh/hhe/
28. [Accessed July 18, 2008] Health Hazard Evaluation report (HETA 87-309-1906), Louisiana-Pacific Corporation, Montana (1988). [Online] http://www.cdc.gov/niosh/hhe/
29. [Accessed July 18, 2008] Hazard Evaluation Technical Assistance report (HETA 89-276-L2093), Lockheed Aeronautical Systems Company, Georgia (1991). [Online] www. http://cdc.gov/niosh/hhe/
30. [Accessed July 18, 2008] Health Hazard Evaluation report (HETA 93-0035-2481), American Buildings Co., Illinois (1995). [Online] http://www.cdc.gov/niosh/hhe/
31. [Accessed September 26, 2008] National Air Quality Emissions Trends Report, 1999 (EPA 454/R-01-004). [Online] http://www.epa.gov/nscep/
32. [Accessed September 26, 2008] Current Industrial Reports: Paint and Allied Products. [Online] http://www.census.gov/mcd/
33. [Accessed July 18, 2008] Performance Evaluation of Respiratory Protective Equipment Used in Paint Spraying Operations. [Online] http://www.cdc.gov/nioshtic-2/
34. Nelson TJ, Wilmes DP, daRoza RA. ANSI Z88.2 (1992): Practices for respiratory protection. Am Ind Hyg Assoc J. 1994; 55:660–662.
35. Caldwell DJ, Armstrong TW, Barone NJ, Suder JA, Evans MJ. Hydrocarbon solvent exposure data: Compilation and analysis of the literature. Am Ind Hyg Assoc J. 2000; 61(6):881–894.
36. Ford DP, Schwartz BS, Powell S, et al. A quantitative approach to the characterization of cumulative and average solvent exposure in paint manufacturing plants. Am Ind Hyg Assoc J. 1991; 52:226–234. [PubMed: 1858665]

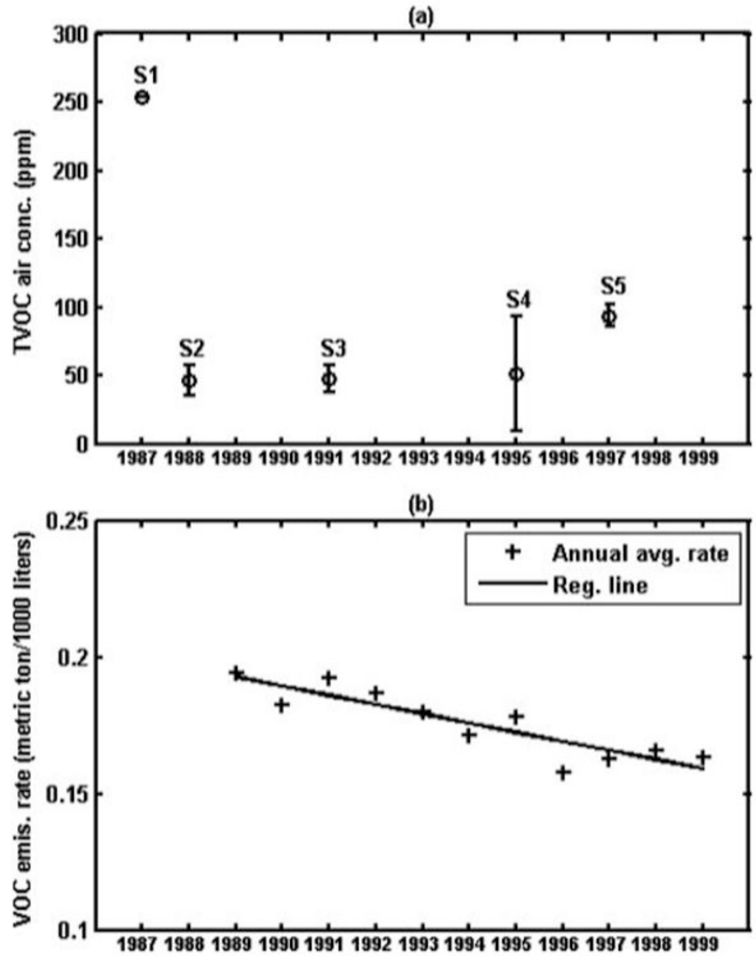

Figure 1.

(a) The historical trend of organic solvent air concentrations (expressed as total VOC concentrations in ppm) in the United States; where S1 (P. Roper[(27)]), S2 (S.A. Lee[(28)]) S3 (Salisbury et al. [(29)]), S4 (Cook and Hoekstra[(30)]), S5 (Bigelow et al. [(13)]). The circle and bar represent mean and standard deviation, respectively. (b) The national temporal trend of VOC emission rates (metric ton/1000 L) of architectural and industrial maintenance coatings from 1989 to 1999 in the United States.

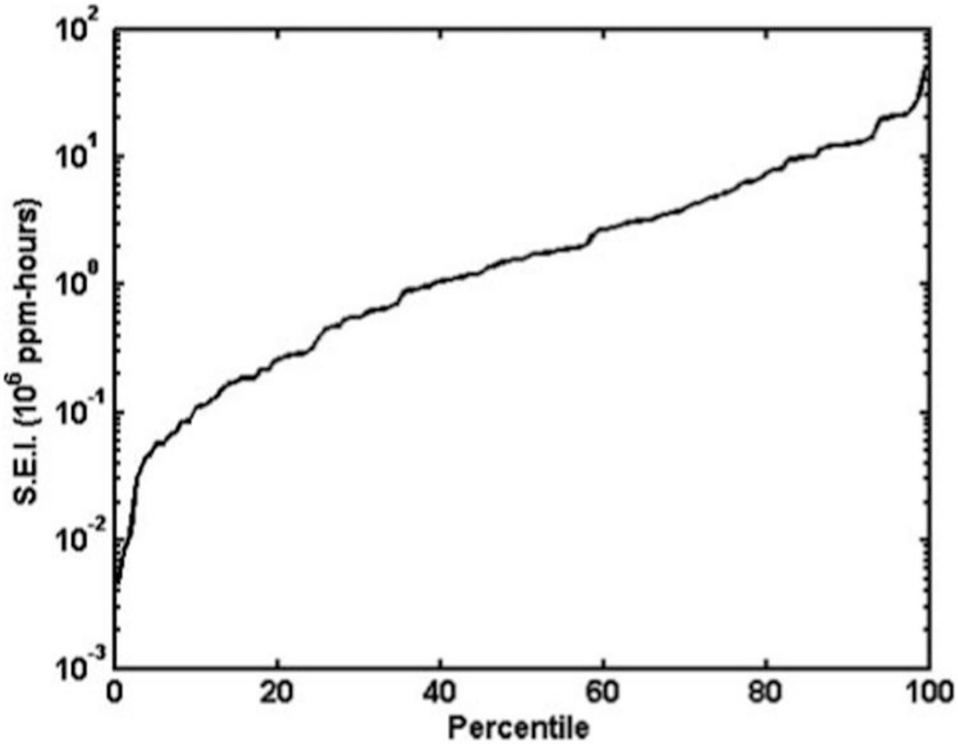

Figure 2.
Cumulative distribution function of the calculated solvent exposure index (10^6 ppm-hr) for the cohort of 125 painters.

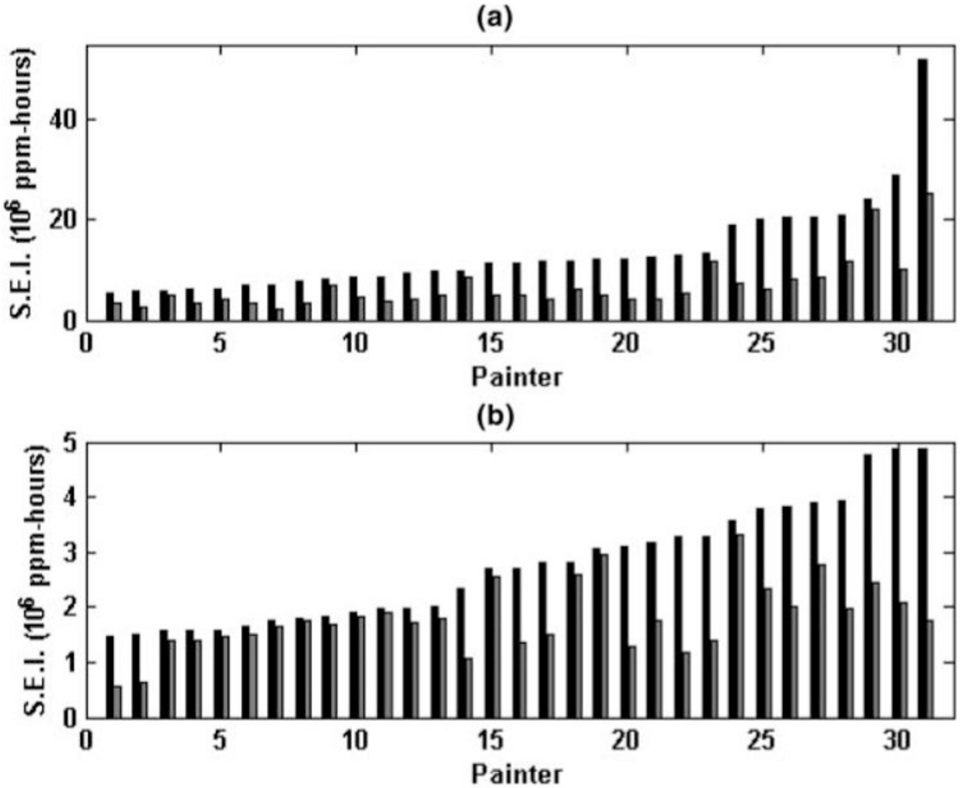

Figure 3.

Comparison of the solvent exposure indices (10^6 ppm-hours) calculated with (black bars) and without (gray bars) the inclusion of historical adjustments for the solvent air concentrations for the painters classified in (a) the 4th exposure quartile and (b) the 3rd exposure quartile based on the scenario of *Solvent air* and *Protection factor*.

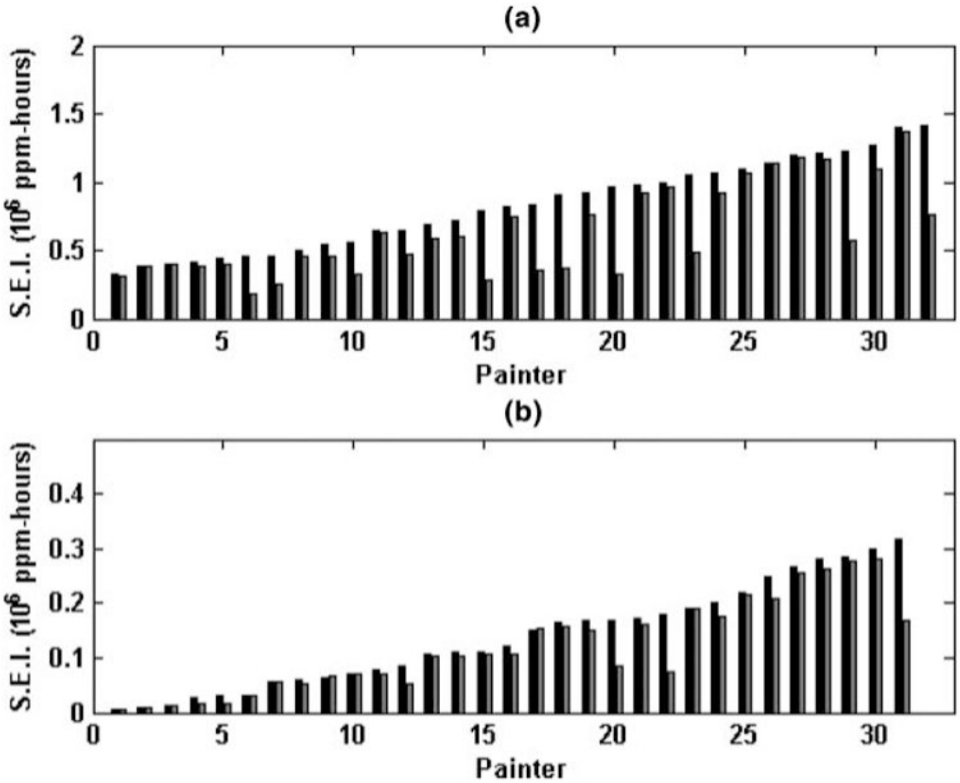

Figure 4.

Comparison of the solvent exposure indices (10^6 ppm-hours) calculated with (black bars) and without (gray bars) the inclusion of historical adjustments for the solvent air concentrations for the painters classified in (a) the 2nd exposure quartile and (b) the 1st exposure quartile based on the scenario of *Solvent air* and *Protection factor*.

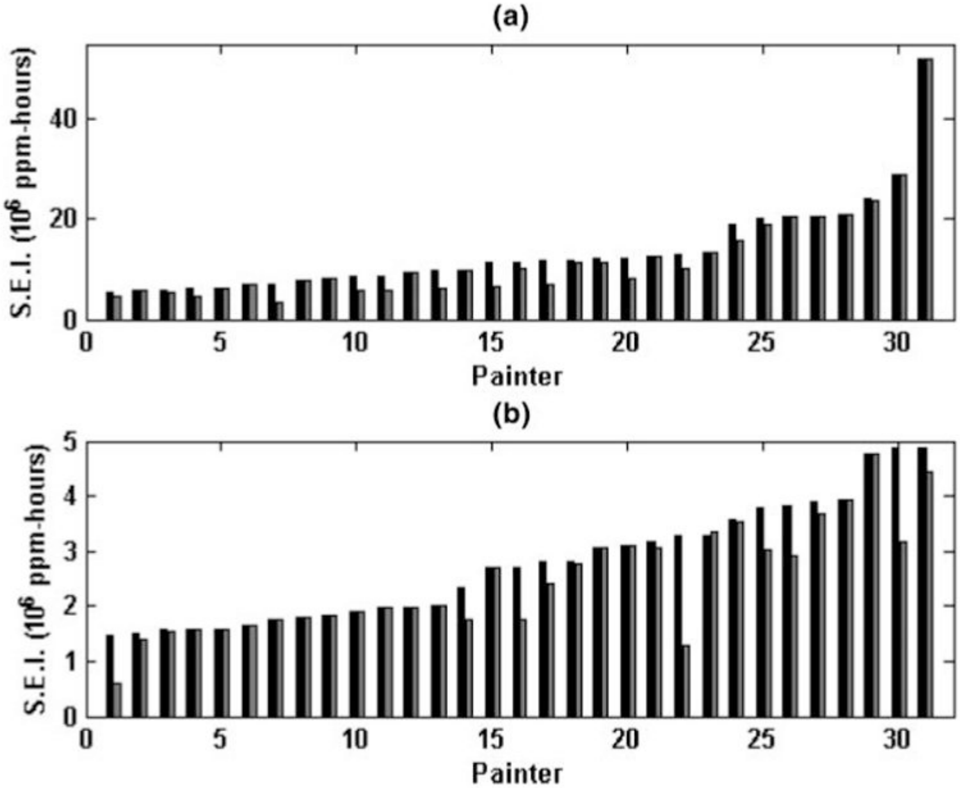

Figure 5.
Comparison of the solvent exposure indices (10^6 ppm-hours) calculated with (black bars) and without (gray bars) the inclusion of historical adjustments for the respirator protection factors for the painters classified in (a) the 4th exposure quartile and (b) the 3rd exposure quartile based on the scenario of *Solvent air* and *Protection factor*.

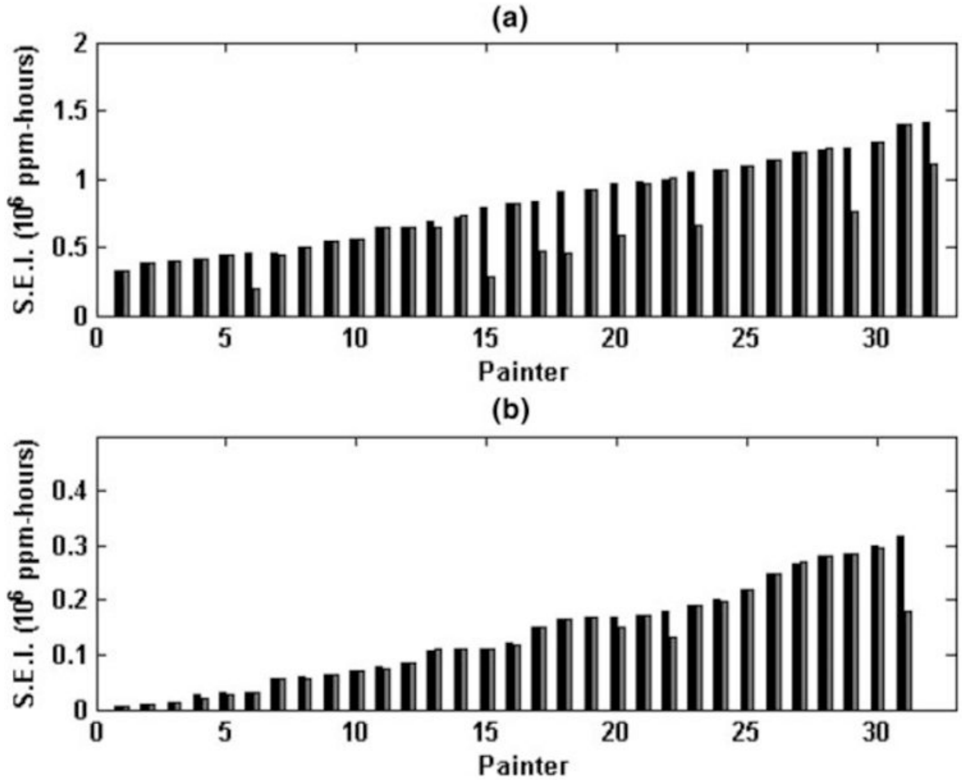

Figure 6.
Comparison of the solvent exposure indices (10^6 ppm-hours) calculated with (black bars) and without (gray bars) the inclusion of historical adjustments for the respirator protection factors for the painters classified in (a) the 2nd exposure quartile and (b) the 1st exposure quartile based on the scenario of *Solvent air* and *Protection factor*.

Table I

List of Exposure Reconstruction Modeling Components to Derive the Solvent Exposure Index for Construction Painters

Category	Component
Cumulative time spent painting	Number of years of using solvent-based paint
	Time spent for different painting activities
	Conversion of qualitative responses to quantitative values for extent of time spent in different painting activities
Air concentrations of organic solvents	Current and historical industrial hygiene measurements (personal and work area air concentrations of solvents)
	Changes of solvent air concentrations over time
	Regulations of VOC emission reduction on industrial maintenance coatings
	Examination of MSDSs for current and past paint compositions
	Historical changes on paint composition
	Characterization of historical trend of solvent air concentrations
Protection factors of respirators	Levels of respirators used by time and painting activity
	Current assigned protection factors of respirators
	Historical assigned protection factors of respirators and regulations
Solvent exposure index	Examination of exposure misclassification of using different exposure metrics as additional variables are added to the calculation

NIH-PA Author Manuscript

NIH-PA Author Manuscript

Table II

Number of Painters in the Cohort Across 5-Year Time Periods from 1980 to 2005

Time Period	2000–2005	1995–2000	1990–1995	1985–1990	1980–1985
Number of painters	125	122	106	76	50

NIH-PA Author Manuscript
NIH-PA Author Manuscript

Table III

Descriptive Statistics of the Solvent Air Concentrations (in ppm) in Painting Activity-Specific Exposure Measurements Collected from the Bridge Work Sites

Chemicals	Maximum	Minimum	Mean/Geometric Mean[A]	SD/Geometric SD[B]
		Spraying Painting (N = 18)		
Aromatics	802.1	96.3	407.2	240.1
Acetates	689.7	0.05	2.7	69.9
Ketones	268.4	0.05	0.8	37.7
		Rolling Painting (N = 14)		
Aromatics	12.8	0.9	6.7	4.6
Acetates	12.8	0.05	0.9	5.9
Ketones	7.6	0.05	0.3	6.9
		Brushing Painting (N = 15)		
Aromatics	2.4	0.3	0.8	0.8
Acetates	0.8	0.05	0.1	2.8
Ketones	1.2	0.05	0.2	3.6

Notes: N is number of samples, SD is standard deviation.

[A]Mean is shown for aromatics; geometric means are shown for acetates and ketones.

[B]Standard deviation is shown for aromatics; geometric standard deviations are shown for acetates and ketones.

NIH-PA Author Manuscript
NIH-PA Author Manuscript

Table IV

Historical Changes of the Contaminant Collection Efficiencies for Four Types of Respirators

	Dust Mask	Full-Face Chemical Cartridge	Half-Face Chemical Cartridge	Supplied-Air Respirator
Before 1990	0	0.75	0.65	0.90
After 1990	0	0.98	0.90	0.999

NIH-PA Author Manuscript
NIH-PA Author Manuscript

Table V

Number of Painters Classified in Exposure Quartiles Using Different Levels of Solvent Exposure Estimates

	1st Quartile	2nd Quartile	3rd Quartile	4th Quartile
(a) Solvent exposure index of *Solvent air* and *Protection factor* (horizontal) vs. *the number of years* using SBP (vertical); Spearman correlation coefficient: 0.55				
1st quartile	15	7	9	0
2nd quartile	10	13	5	4
3rd quartile	5	8	8	10
4th quartile	1	4	9	17
(b) Solvent exposure indices of *Solvent Air* and *Protection factor* (horizontal) vs. *Protection factor adjusted* (vertical); Spearman correlation coefficient: 0.98				
1st quartile	29	2	0	0
2nd quartile	2	27	3	0
3rd quartile	0	3	26	2
4th quartile	0	0	2	29
(c) Solvent exposure indices of *Solvent air* and *Protection factor* (horizontal) vs.*Solvent air adjusted* (vertical); Spearman correlation coefficient: 0.99				
1st quartile	29	2	0	0
2nd quartile	2	29	1	0
3rd quartile	0	1	28	2
4th quartile	0	0	2	29

Table VI

Percentages of Painters Wearing Respirators Almost All the Time

Time Period	Spraying (%)	Rolling (%)	Brushing (%)
2000–2005	61.8	31.3	29.8
1995–1999	63.6	34.7	28.0
1990–1994	57.0	37.2	30.2
1985–1989	45.3	26.4	22.6
1980–1984	34.5	17.2	13.8

Note: Respirators included full-face chemical cartridge, half-face chemical cartridge, and supplied-air.